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14. ABSTRACT

Developed an ADI method to efficiently solve the ice momentum equations associated with a lead-based viscous plastic rheology. Implemented the ADI solver in a dynamic thermodynamic sea-ice model in spherical coordinates. Also developed mathematical formulations for viscous plastic rheologies using teardrop and parabolic lens yield curves with or without incorporating tensile stress. These rheologies, together with the elliptical yield curve, have been numerically implemented in a 10 km. high-resolution 12-category thickness and enthalpy distribution (TED) model for the Arctic Ocean. Did three model runs with these 3 yield curves, driven by atmospheric forcing from 1987-1999. Conducted model runs with a corresponding 40-km resolution model using 4 plastic yield curves. Incorporated an optimal interpolation data assimilation procedure in a TED sea-ice model. Investigated effects of assimilating buoy drift data and satellite ice motion data on modeling Arctic sea ice.

15. SUBJECT TERMS

Arctic, ice dynamics, ice mechanics, numerical method, lead-based rheologies

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Toward Construction of an Efficient, Lead-Resolving PIPS Model

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LONG-TERM GOALS

Our long-term goals are to develop and implement lead-based sea ice rheologies into a high-resolution anisotropic sea ice model that is able to efficiently simulate and predict the initialization and propagation of oriented leads and ridges of sea ice. Our particular interest is to provide such a lead-resolving sea ice model for the Navy's Polar Ice Prediction System (PIPS) for high-resolution, large-scale sea ice forecasting. We are also interested in using the model to understand the dynamic and thermodynamic sea ice processes that trigger leads and ridges to form and propagate in time and space in relation to atmospheric and oceanic forcing. In addition, we wish to use the model to study the air-sea exchange through leads in relation to their geometry and thickness.

OBJECTIVES

The Navy's next-generation PIPS aims at high-resolution (9-10 km), lead-resolving forecasts of sea ice and ambient noise in most ice-covered regions in the northern hemisphere. To help meet such a goal, we will develop a new numerical model for sea ice dynamics that uses an alternating direction implicit (ADI) method to efficiently solve ice momentum equations based on a spherical coordinate system. We will also develop mathematical formulations and numerical schemes for lead-based rheologies that may be introduced in an isotropic sea ice model to predict the formation and propagation of oriented leads and ridges of sea ice. We will incorporate the related rheologies in a 10-km high-resolution sea ice model, driven by realistic atmospheric forcing, to examine how they behave in actually simulating and predicting leads and ridges. The modeled leads will be compared with satellite observed leads or cracks.

APPROACH

Sea ice is characterized by oriented leads, cracks, and ridges, which determine the anisotropic properties of sea ice flow. To completely capture the anisotropic properties of sea ice requires a fully anisotropic model with a memory of past oriented leads. This, at present, would be difficult for large-scale sea ice models to accomplish because of the lack of theoretical and numerical readiness. Our approach was

based on the work of Hibler and Schulson (1997). They considered sea ice to be a composite system that consists of relatively strong thick ice embedded with weak thin-ice leads. Both the thick-ice and the thin-ice leads are designed to follow a viscous plastic ice rheology. Hibler and Schulson were then able to achieve "isotropic realizations" in "dynamically treating" the oriented leads, in which lead or ridge formation could be captured using isotropic but lead-based ice rheologies. Hibler and Schulson suggested two rheologies, related to two different conditions of anisotropic ice composite, potentially useful in estimating the occurrence and orientation of leads. One is represented by a teardrop-like plastic yield curve, the other a lens-like plastic yield curve. An important question arose to researchers: can these lead-based but isotropic viscous plastic rheologies capture the anisotropic properties of sea ice if implemented in large-scale isotropic sea ice models? To answer this question, we wish to implement the above-mentioned rheologies, in addition to the widely used elliptical yield curve (Hibler, 1979), in a high-resolution isotropic sea ice model, and to examine the effectiveness of these rheologies in predicting the formation and propagation of leads and ridges under realistic conditions of surface atmospheric forcing. If the rheologies are effective, then they can be directly incorporated into PIPS for lead-resolving sea ice forecasts. However, as observed through satellite images, leads, cracks, and ridges are generally narrow faults. This raises another question: what model resolution is appropriate to resolve such narrow features? In order to understand the scale effects on modeling leads and ridges, we wish to run a corresponding sea-ice model with a 40-km resolution and compare its results with those from the 10-km resolution model. Finally, we realize that great advances have been made in polar observational capabilities in recent years that have led to a rich collection of buoy and satellite observations of ice motion. It is useful to incorporate these observations in a forecast system such as the PIPS. We wish to develop a model with data assimilation capability and examine how assimilating buoy and satellite observations improves the modeling of ice motion, stress, and deformation, and therefore ice leads and ridges.

WORK COMPLETED

We have developed an ADI method to efficiently solve the ice momentum equations associated with a lead-based viscous plastic rheology. The ADI solver has been implemented in a dynamic thermodynamic sea-ice model in spherical coordinates. Also, we have developed mathematical formulations for viscous plastic rheologies using teardrop and parabolic lens yield curves with or without incorporating tensile stress. These two rheologies, together with the elliptical yield curve, have been numerically implemented in a high-resolution (10 km, close to the current PIPS resolution) 12-category thickness and enthalpy distribution (TED) sea ice model (Zhang and Rothrock, 2001) for the Arctic Ocean. Driven by atmospheric forcing from 1987 to 1999, three model runs with these three yield curves, respectively, have been carried out. Also conducted have been a series of model runs with a corresponding 40-km resolution ice-ocean model using 4 plastic yield curves – elliptical, teardrop, lens, and coulombic (Hibler and Schulson, 2000) yield curves. In addition, we have incorporated an optimal interpolation data assimilation procedure in a TED sea-ice model. Using this assimilation procedure, we have investigated the effects of assimilating buoy drift data and satellite ice motion data on modeling Arctic sea ice. The effects of data assimilation in the TED model have been described in a paper submitted to the Journal of Geophysical Research (Zhang et al., 2001). A paper that describes the TED model has been published in the Journal of Physical Oceanography (Zhang and Rothrock, 2001). In collaboration with Ron Lindsay, we have compared model simulated ice deformation with RGPS (The RADAR-SAT Geophysical Processor System) derived ice deformation. A manuscript with the comparison results has been submitted to Atmosphere-Ocean. Finally, work is underway to examine the effect of tensile stress on simulating sea ice using the four yield curves with or without allowing tensile stress.

RESULTS

We found that the above-mentioned three rheologies (ellipse, teardrop, and lens), when implemented in an isotropic sea ice model with a 10-km resolution, were able to simulate the initialization and propagation of major leads and ridges, represented by strong, long shear zones, especially those initiated at coastal boundaries (see Figures 1a, 1b, and 1c and also see our results reported in Overland and Ukita, 2000). Isotropic viscous plastic rheologies appear able to capture basic anisotropic properties of sea ice with sufficiently fine model resolution. Comparing model results with RGPS ice deformation data, we saw indication that model resolution finer than 10 km may be needed in order to capture more leads or ridges observed by satellite sensors. With 40-km resolution, the model either fails to capture some of the major leads that are seen with the 10-km model or creates shear zones that are less sharp (Figure 1d). This further stresses the importance of model resolution for predicting ice faults.

The shear deformation patterns created by those three different rheologies are not necessarily the same. Some leads or ridges they create are similar, some differ. Therefore additional investigation is necessary to determine which rheology is relatively more realistic.

We also found that assimilating ice motion observations in the TED model significantly improves the modeled ice motion with a reduced error and an increased correlation with observations. Data assimilation also considerably increases ice deformation and, hence, ice lead opening and ridging (Figure 2). The assimilation-enhanced ice lead opening and ridging in turn result in more spatial variability of ice thickness that agrees better with the observed ice thickness taken along four tracks of recent (1993–1997) submarine cruises in the Arctic.

Lab tests indicate that ice can resist certain tensile stress. We have developed mathematical formulations that allow teardrop and lens yield curves to incorporate tensile stress, which may be useful for better prediction of leads and ridges. Using a 40-km resolution ice-ocean model, we have found that incorporation of tensile stress has significant impact on the simulation of ice motion and thickness. With tensile stress, sea ice moves slower, which leads to less ice export at Fram Strait and more ice staying inside the Arctic. Less clear is what role tensile stress would play in high-resolution modeling of leads and ridges. A paper is in preparation to report the results.

IMPACT/APPLICATION

Our model results have shown that using isotropic viscous plastic rheologies in fine-resolution (in the scale of 10 km) sea ice models are likely to capture major oriented leads and ridges in the Arctic. Given that a 40-km resolution model behaves poorly in capturing narrow leads and ridges, we feel that using finer model resolution (~ 5 km) is likely to further improve the model's capability of resolving narrow ice faults. Our work also suggests the importance of data assimilation, which enhances the calculation of ice motion, deformation, lead opening, and ridging. Lead-resolving modeling would improve the calculation of ice dynamics and therefore forecasting of sea ice. Reliable prediction of leads and ridges is also important for the Navy's operations in the ice-covered oceans. In addition, modeling lead formation and propagation is also useful for understanding the air-sea exchange in the polar regions, which is important for climate studies.
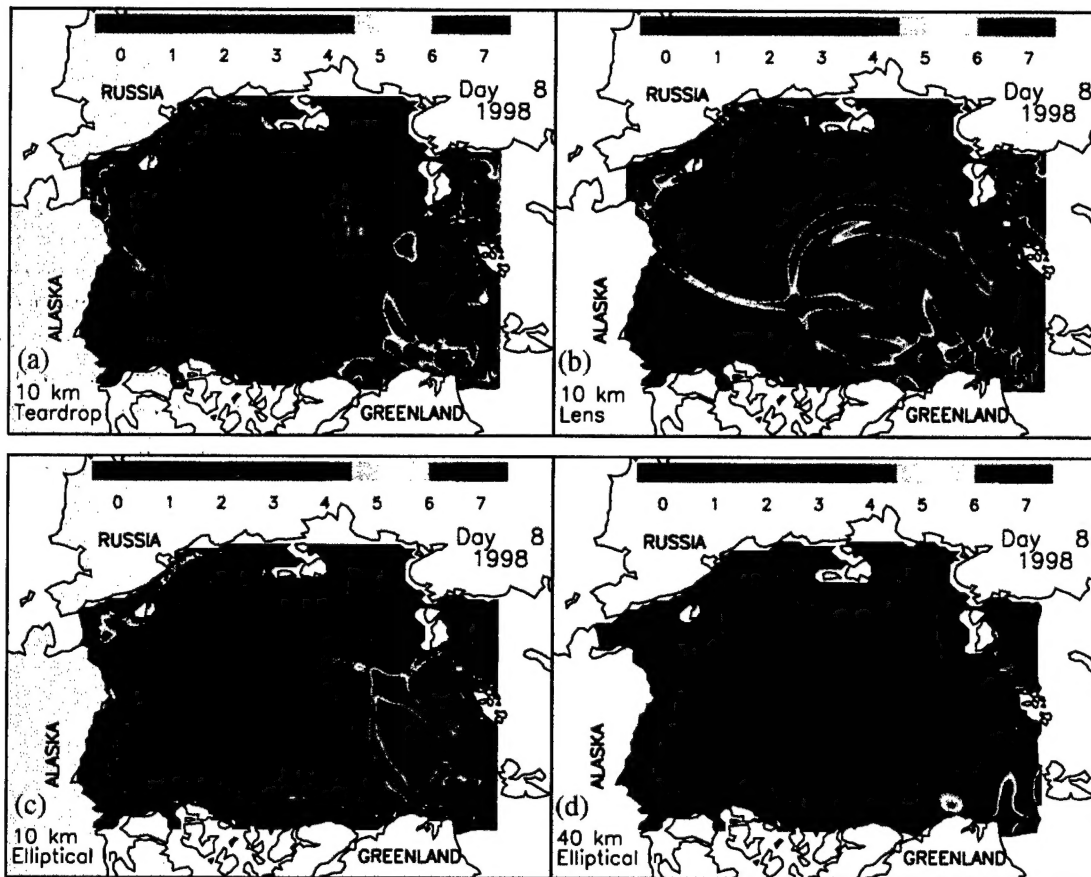
Figure 1. Modeled shear deformation (0.5%/day) of sea ice in the Arctic Ocean for January 8, 1998 using a 10-km resolution TED model with (a) a teardrop yield curve, (b) a lens yield curve, and (c) an elliptical yield curve, and using (d) a 40-km resolution TED model with an elliptical yield curve. The figure shows that the 10-km resolution sea ice model, with various viscous plastic rheologies, creates long shear deformation zones, whereas the 40-km model poorly simulates ice faults. This indicates that high-resolution models may be used to effectively simulate major oriented leads, cracks, or ridges.
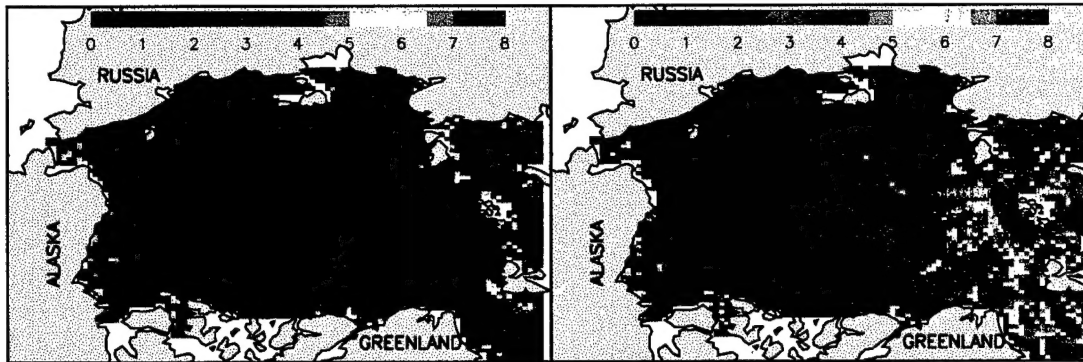
Figure 2. Modeled shear deformation (%/day) of sea ice in the Arctic Ocean for January 1, 1993, using a 40-km resolution TED model with (right panel) or without (left panel) assimilating buoy motion and satellite ice motion data. This figure shows that data assimilation significantly enhances the calculation of ice deformation and, therefore, ice lead opening and ridging.

TRANSITIONS

Employing the viscous plastic rheology with an elliptical yield curve, the current PIPS model, to our knowledge, uses the sea ice dynamics model that was developed by Dr. Bill Hibler and one of us (Zhang and Hibler, 1997). We have provided the PIPS model development group at the Naval Postgraduate School with a new sea ice model using an alternating direction implicit technique to efficiently solve ice dynamics in a spherical coordinate system (Zhang and Rothrock, 2000), which may be used in the PIPS. The ice model has also been provided to the global climate modeling group at the Goddard Institute for Space Studies. Further, it has been placed in a ftp site for other PIPS researchers to access. Also placed in the ftp site are computer codes implementing the teardrop and lens yield curves.

RELATED PROJECTS

Drs. Axel Achweiger and Ruth Preller and one of us (Zhang) are investigating the effects of surface atmospheric forcing on sea ice forecasting. Accurate surface atmospheric forcing is essential to the quality of sea ice forecasting.

PUBLICATIONS

Zhang, J., and D.A. Rothrock, 2001: A thickness and enthalpy distribution sea-ice model, *J. Phys. Oceanogr., 31*, 2986–3001.

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